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Thermal and filtration performance assessment of a dynamic insulation system

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Abstract

Improvement in the thermal performance of the envelope in Nearly Zero Energy Buildings could lead to the paradoxical need for high energy consumption to handle the internal moisture load and pollutants by using mechanical equipments. An alternative passive strategy is related to the use of breathing envelopes integrating a "dynamic insulation". In these systems, outdoor air is drawn into the building and passes through a porous insulation material being in this way pre-heated and filtered. This paper provides experimental and analytical results on the thermal and filtration performance of a dynamic insulation for building envelope for application in temperate climate.

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Keywords: dynamic insulation; NZEB; air filtration; breathing building; IAQ

1. Introduction

The thermal performance of the envelope is primary for the construction of Nearly Zero Energy Buildings. As a result, several countries have increased their airtightness and thermal resistance requirements in buildings, to minimize heat dispersions by conduction and infiltration as much as possible. Despite the fact that over the last decades a better Indoor Air Quality (IAQ) in living spaces is required, these strategies could lead to high internal moisture load and pollutants in combination with an unsuitable ventilation system, with consequences for durability of materials and inhabitants' comfort and health [1,2]. Improvement in the envelope performance could then lead to the paradoxical need for high-energy consumption to manage the IAQ by using ventilation equipments.

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Nevertheless, these equipments may have considerable costs both in the installation phase as well as during their use. Besides, their installation is not always possible in old buildings. Consequently, in the future NZEBs there is a growing need to develop more passive and less energy intensive methods of moderating the indoor environment.

In recent decades, some authors have focused on a strategy related to the use of “breathing envelopes” integrating a “dynamic insulation”, mainly in cold climates[3–6]. In these systems, outdoor air is drawn into the building through a porous insulation material, being in this way pre-heated and filtered. The technology of the Dynamic Insulation Wall (DIW) bases its effectiveness on the fact that a part of the heat lost by conduction can be recovered from the air flow of incoming ventilation, perpendicularly to the insulation and with the direction opposite the heat flow [7] (Fig. 1). The building envelope thus becomes a kind of heat recovery unit through which the air flow entering the building is activated by a pressure difference generated naturally (stack effect and wind pressure) or mechanically (by fans) [5]. This paper will provide experimental and analytical results on the thermal and filtration performance of a DIW for building retrofit in a temperate climate as the Italian one, which could ensure adequate air change, thermal transmittance and filtration of pollutants. These assessments are necessary prior to the optimization of the design of the DIW and the construction of a real-scale device for testing under ambient conditions.

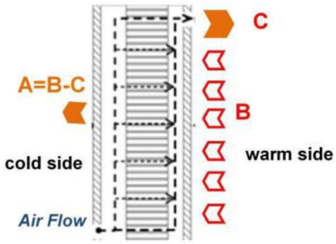

Fig. 1. Operation scheme of a Dynamic Insulation Wall.

2. Methodology

2.1. Description of the Dynamic Insulation Wall (DIW)

The DIW presented here is configured as an “interior wall panel” for building retrofit, which consists of different functional layers: an interior plasterboard, an air gap, the permeable insulating material, a second air gap facing the outer layer, which in the case of building renovation can be variably composed. The entrance of the external air is ensured by openings installed at the base of the wall, while the outlet is achieved with openings located at the top of the inside panel. In this study, we compared the filtration performance of two different porous materials to be used as insulation in the DIW: cellulose and polyester fiber, whose main features are shown in Table 1.

Table 1. Thermal and physical properties of the two porous insulations: cellulose and polyester fiber.

	Cellulose	Polyester fiber
Thickness [m]	0,095	0,1
Density ρ [kg/m³]	47	40
Air Permeability Φ [m²/sPa]	0,000055	0,000086
Thermal conductivity λ [W/mK]	0,0380	0,0389

2.2. The evaluation of the filtration efficiency

Both permeable insulating materials, cellulose and polyester fiber, have a fibrous nature, which makes them ideal candidates for the filtration of the atmospheric particulate matter (PM) in the air volume expected to ensure the ventilation of the indoor environment. The filtration efficiency has been evaluated through a continuous analysis using an optical particle counter (OPC) FLUKE 983 with a counter efficiency of 50% for 0,3 µm particles and 100% for >0,45 µm particles. The OPC returns the cumulative sum of the particles according to their equivalent diameter, contained in 2.83 liters of air drawn in one minute.

A synthetic powder composed of talc, zinc oxide, hydrated silica, liquid paraffin was realized as a source of particulates with equivalent diameter of 2, 5, 10 µm. The insulating samples on special wooden frames were positioned within a test chamber, connected to a system of air supply and suction with a speed of 10^{-2} m/s. Through the air supply, a controlled precipitation of the synthetic powder was made using a funnel dispenser. At the center of the test chamber, the air sampling tube of the OPC was positioned. During a first experimental phase, 5 measurements with controlled dust concentration were carried out to register the amount of PM in the test chamber before the installation of the filter. During a second phase, after the filter installation, 5 new measurements were carried out to detect via optical counter the concentration of particulates.

2.3. The evaluation of the thermal performance

The thermal performance of DIW has been assessed for cellulose insulation through a two-dimensional modeling with the simulation program for the calculation of heat and air transport Delphin 5.6.8, taking into account different climatic conditions. The model has been calibrated against experimental results obtained on a DIW small prototype using a Hot Box test facility, built according to EN 12667:2001 and modified to simulate an airflow rate through the dynamic insulation. The test apparatus consisted of an insulated chamber at whose extremes two aluminum heating and cooling plates 50x50 cm were positioned. The sample of cellulose insulation has been installed on a wooden frame (sized 50x50x10 cm thickness), stuck to two additional wooden frames (sized 50x50x6 cm thickness), which simulated the presence of two air gaps located upstream and downstream of the insulation, as well as in the real DIW. These cavities were connected to pipes for the input and the suction of the air in the system, in order to simulate the passage of air through the dynamic insulation, in a uniform and unidirectional way. The supply air has been pre-cooled through a heat exchanger to simulate the passage of cold winter air in the system.

6 thermal resistances (PT100 Lsi-Lastem, accuracy +/-0.15°C) and 4 heat flow meters (HFP01 Hukseflux, accuracy +/-5%) were placed on the surfaces of the plates and the insulating according to the scheme in Fig. 2. The probes were connected to a HP AGILENT 34970A data acquisition-switch unit and data were stored every minute.

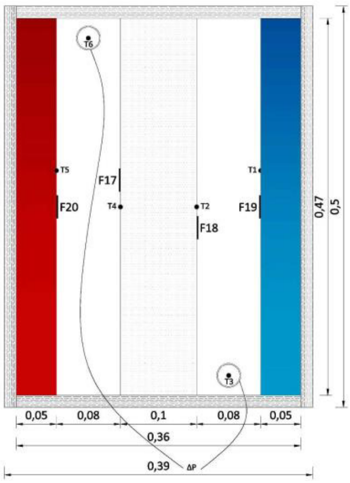

Fig. 2. Positioning of the temperatures (T) and heat flow (F) probes in the DIW prototype for the Hot Box test.

Tests were carried out at steady-state temperatures, according to the two phases presented in Table 2: a phase at constant airflow rate and variable temperature gradient, and a phase at constant temperature gradient and variable airflow rate. For the calibration of the analytical model, three conditions were chosen (gray in Table 2).

Table 2. Test conditions during two phases. In grey the conditions chosen for the calibration of the analytical model.

Test Conditions					
	Experimental cases	Te, T1 [°C]	Ti, T5 [°C]	Pe [Pa]	Pi [Pa]
1st phase (Δt)	1	18,18	22,71	101325,00	101323,41
	2	15,20	22,39	101325,00	101323,40
	3	15,28	27,62	101325,00	101323,37
	4	15,67	32,16	101325,00	101323,32
2nd phase (Δv)	5	15,20	22,39	101325,00	101323,40
	6	15,38	21,99	101325,00	101317,48
	7	14,73	21,35	101325,00	101320,60

The analytical model was then extended to a real-scale DIW, with the stratigraphy reported in Table 3, also in comparison with a conventional wall (same stratigraphy, without air outlets). Simulations were carried out in 3 Italian climatic zones and the insulation thickness was calculated according to Italian law (D.Lgs. 311/2006).

Table 3. Stratigraphy of the simulated DIW.

Material	**Thickness s**	**Thermal conductivity**	**Heat capacity c**	**Density**	**Air permeability**	**Vapour**
External existing wall	0,35	0,385	833	1200	-	45
Air Gap	0,08	0,278	1000	1,29	1	0,35
Cellulose Insulation	0,12 (Bolzano) 0,10 (Ancona) 0,08 (Palermo)	0,038	2544	45	0,0000680556	5
Air Gap	0,08	0,278	1000	1,29	1	0,35
Internal Plasterboard	0,012	0,200	850	850	-	10

The climatic files of the software for the different climates have been used to set the boundary conditions of the annual simulations. The values of temperature and relative humidity inside have been set respectively at 20°C and 60%. External atmospheric pressures were set constant and extracted from data of the Italian Air Force. The pressures of the indoor air were obtained by evaluating the contributions of the stack effect, the wind pressure on the wall, the pressure losses in the outlets o and through the permeable material.

3. Results

3.1. Evaluation of the filtration efficiency

The efficiency (E) of PM capture of each sample was obtained by the following eq.1:

$$E[\%] = \frac{Q_{DT}}{Q_{DR}} \bullet 100 = \frac{C_U}{C_D} \bullet 100 \qquad (1)$$

Where Q_{DT} is the amount of dust retained; Q_{DR} is the amount of dust released; C_U is the concentration upstream of filter; C_D is the concentration downstream of filter. Table 4 report measured E of cellulose and polyester fiber. It can be observed a similarity in performance of both materials, in particular for PM5. The polyester shows a better behavior in the capture of PM10 (100%) compared to cellulose (99.94%). The most significant difference occurs for the values of E relating to PM2, which is the particulate most dangerous for human health. Cellulose is able to guarantee a percentage efficiency equal to 99.94%, while polyester reaches 99.41%. Consequently, we decided to carry out the evaluation of the thermal performance of the DIW with cellulose insulation, which offers a high filtration performance for all PM diameters.

Table 4 Filtration efficiency of PM capture of each insulation sample (cellulose and polyester fiber)

	Particles diameter [μm]	E1 [%]	E2 [%]	E3 [%]	E4 [%]	E5 [%]	Averaged Efficiency [%]	Standard Deviation [%]
Cellulose	10	99.93	99.96	99.91	99.91	100.00	99.94	0.04
	5	99.98	99.99	99.92	99.94	100.00	99.96	0.03
	2	99.96	99.96	99.91	99.94	99.98	99.94	0.03
Polyester Fiber	10	100.00	100.00	100.00	100.00	100.00	100.00	0.00
	5	99.95	99.97	99.93	99.94	100.00	99.95	0.03
	2	99.41	99.59	99.39	99.24	99.30	99.41	0.13

3.2. Experimental and analytical evaluation of the thermal performance

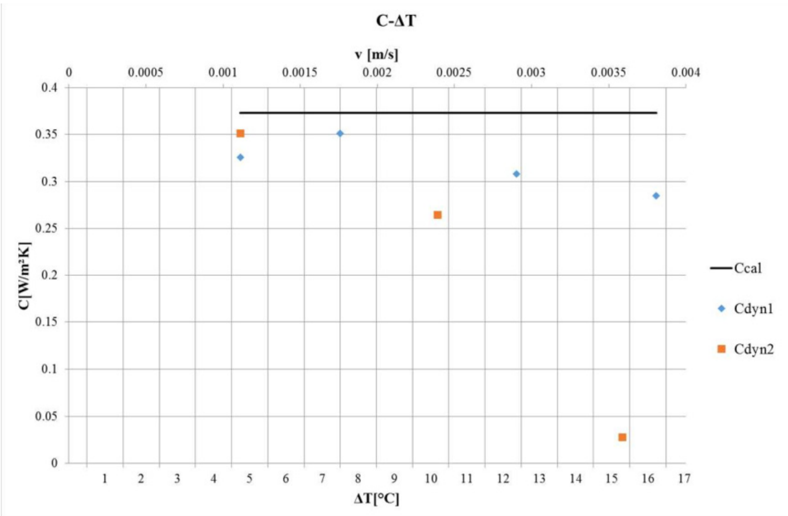

Fig. 3. Dynamic thermal conductance of DIW with cellulose insulation at the different phases of the experimentation.

Given the mean heat flow (F19) and the difference of surface temperatures on the plates (T1-T5), obtained with the hot box test, we estimated the dynamic thermal conductance of DIW with cellulose insulation, using the Average Method of standard ISO 9869: 1994. The graph in Fig. 3 shows the values of the conductance at the different phases of the experimentation, in relation to the temperature difference (Cdyn1) and the air flow rate (Cdyn2), also compared with the calculated conductance (Ccal). From the graph, we can observe a variation of the dynamic conductance of cellulose with temperature difference. The experimental conductance assumes values similar to the calculated conductance for low air speed and decreases with the increasing of the airflow in agreement with results in literature. Experimental data were used for the calibration of the analytical model, obtaining a good approximation of the temperatures in the different interfaces of the DIW modeled (Fig. 4).

The simulations in dynamic conditions allowed obtaining the thermal transmittance values of the DIW in comparison with the traditional wall. Table 5 shows the values averaged with the method of ISO 9869: 1994 for the three Italian climatic zones. According to this assessment, the DIW allows to obtain significantly lower thermal transmittances than those obtained by the traditional wall, especially in the colder climate (55% reduction in Bolzano).

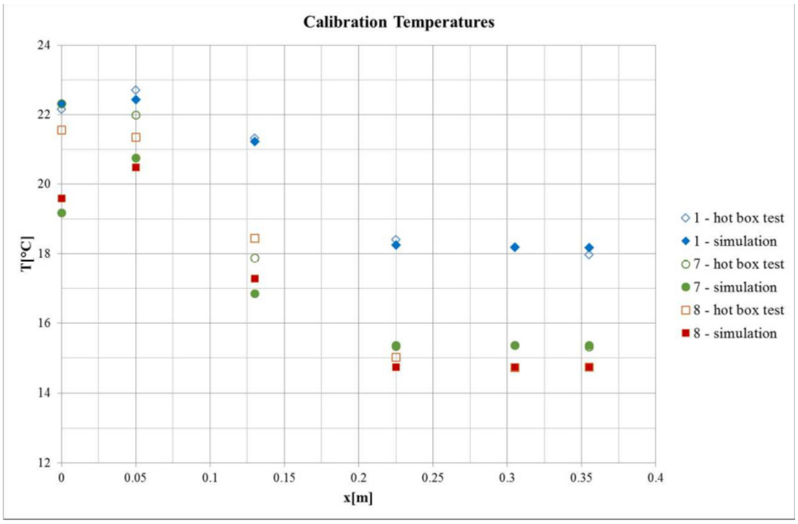

Fig. 4. Comparison of measured and calculated values for temperatures in different depths of the DIW.

Table 5. Average thermal transmittance values of the DIW in comparison with the traditional wall for three Italian climatic zones.

Climatic zone	Town	Heating degree days	Udyn [W/m²K]	Ustat [W/m²K]	Ulim [W/m²K]
B	Palermo	601 - 901	0.232	0.325	0.48
D	Ancona	1401 - 2101	0.163	0.226	0.36
F	Bolzano	> 3000	0.105	0.232	0.33

4. Conclusion

In this paper, we present the preliminary assessments for the realization of a prototype of DIW that could be used in temperate climates as the Italian one. The fibrous insulating material chosen at this aim is cellulose, which compared with the polyester fiber manifests best PM filtering capacity. Simulation results on thermal performance of DIW showed that during the heating season it allows significant reductions of the stationary thermal transmittance of the envelope (until 55% in the colder climate), which predicts promising future applications. Nevertheless, the performance in cooling season should be further investigate to declare dynamic insulation an effective solution for application in temperate climate.

5. References

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